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DIGITAL MATURITY AND PORT PERFORMANCE IN AN EMERGING ECONOMY: THE CONDITIONING ROLES OF DIGITAL SKILLS AND PORT COMMUNITY GOVERNANCE

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Abstract:
Port digitalisation is widely promoted as a lever of port performance, yet evidence remains dispersed and drawn mostly from European and Asian ports. Drawing on the information technology business value perspective, complementarity theory and the dynamic capabilities view, this study examines whether the digital maturity of a port community is associated with four dimensions of port performance — operational, economic, environmental and social — and whether this association is transmitted by digital dynamic capabilities and conditioned by digital skills and port community governance. Survey data from 150 members of the port communities of Tanger Med and of the ports managed by the Moroccan National Ports Agency, collected between March and May 2026, were analysed with partial least squares structural equation modelling. Digital maturity is positively associated with economic ($\beta = 0.419$), environmental ($\beta = 0.413$) and operational ($\beta = 0.344$) performance, whereas its association with social performance is not significant. Digital skills strengthen the association with operational and economic performance, and governance strengthens the association with economic performance while being directly associated with operational performance. Johnson–Neyman analysis shows that digital maturity is not associated with better perceived performance among respondents reporting the weakest skills or coordination. Contrary to expectations, the digital dynamic capabilities of community members do not mediate the relationship, a precisely estimated null result. These cross-sectional associations, robust to clustered and multilevel inference, a formative specification and multiple-testing correction, suggest that digital investments are linked to higher perceived performance only when coupled with user skills and community-level coordination.

Keywords: port digitalisation; port performance; digital skills; port community governance; Morocco.

Introduction

Ports are no longer conceived merely as interfaces between sea and land transport but as elements of value-driven supply chains whose contribution depends on how smoothly cargo, ships and information flow through them (Bichou & Gray, 2004; Robinson, 2002). Port efficiency has been shown to be a determinant of maritime transport costs of a magnitude comparable to geographical distance (Clark et al., 2004), which makes port performance a matter of national competitiveness. Within this perspective, digitalisation has become one of the main levers of port transformation. Port information systems have expanded from vessel-call and terminal management to port community systems (PCS) connecting all actors of port passage, and further to automation, the Internet of Things, analytics and artificial intelligence (Heilig & Voß, 2017). The digital transformation of maritime transport is presented as a response to the demands for speed, reliability and sustainability in supply chains (Tijan et al., 2021).

Despite this enthusiasm, the evidence on the performance effects of port digitalisation is far from settled. Some studies associate port community systems with operational gains (Caldeirinha et al., 2020) or estimate traffic increases following a port's digital transformation (Li et al., 2025). Others report strong but non-causal correlations between digital maturity and efficiency (Nguyen & Pham, 2026), and some even find a negative association between information sharing and the efficiency of large ports (Yen et al., 2023). This dispersion echoes the productivity paradox of information technology (Brynjolfsson, 1993) and the argument that the value of information technology depends on complementary organisational resources and on the context in which it is deployed (Brynjolfsson & Hitt, 2000; Melville et al., 2004). The main research problem is therefore not whether ports should digitalise, but under which conditions digitalisation is associated with better performance — a question that the port literature has seldom tested empirically. Existing studies rarely test mediating mechanisms and moderating conditions together, focus mainly on operational outcomes, and under-represent African and emerging-economy ports (Almeida & Okon, 2025; Sakita et al., 2024).

Morocco offers a particularly informative setting for addressing this problem. Ports handle about 98% of the country's foreign trade (Ministère de l'Équipement et des Transports, 2011), and national port throughput, including transhipment, reached 262.6 million tonnes in 2025 (Finances News Hebdo, 2026). The Moroccan port system combines a recognised lead in procedural digitalisation — the PortNet single window

has been cited by the United Nations Conference on Trade and Development (UNCTAD) as a model of digitalisation and trade facilitation (Portail national du Royaume du Maroc, 2025) — with a marked duality of performance: Tanger Med ranks among the top container ports worldwide in the Container Port Performance Index (World Bank & S&P Global Market Intelligence, 2025), whereas ports managed by the National Ports Agency (Agence Nationale des Ports, ANP) were reported far lower in the same ranking (Oukerzaz, 2025).

Accordingly, this study addresses the following research question: **to what extent, and under which conditions, is the digital maturity of a port community associated with the operational, economic, environmental and social performance of its port?** Three sub-questions follow: (a) Is digital maturity associated with each dimension of port performance? (b) Is this association transmitted by the digital dynamic capabilities of community members? (c) Is it conditioned by digital skills and by the quality of port community governance?

The study makes three contributions. First, it tests, within a single model, a mediating mechanism and two moderating conditions of the digitalisation–performance relationship, combining the dynamic capabilities view (Teece, 2007; Warner & Wäger, 2019) with complementarity theory (Brynjolfsson & Hitt, 2000). Second, it covers the four dimensions of port performance in an emerging African economy, a context that is under-represented in the literature. Third, it subjects the results to an unusually extensive set of robustness checks — correction for multiple testing, clustered and multilevel inference accounting for respondents nested in ports, Johnson–Neyman regions of significance and an alternative formative specification — which allows robust findings to be distinguished from fragile ones.

The remainder of the article is structured as follows. Section 1 reviews the literature and develops the hypotheses. Section 2 presents the research setting, data and methods. Section 3 reports the results. Section 4 discusses the findings and their implications, and the final section concludes with recommendations, limitations and avenues for future research.

1. Literature review and hypotheses

1.1. Theoretical foundations

Three complementary perspectives explain how digital technologies may relate to port performance. Transaction cost economics suggests that digital platforms reduce the costs of searching, coordinating and controlling exchanges between independent organisations (Williamson, 1979), which is particularly relevant for a port community made up of legally independent actors with partly divergent interests (Heilig et al., 2017). Information processing theory holds that organisations facing uncertainty must either reduce their need for information processing or increase their capacity to process information (Galbraith, 1974); port community systems and real-time tracking increase this capacity. The integrative model of information technology business value proposed by Melville et al. (2004) adds that technology creates value only in combination with complementary organisational resources and within a supportive environment.

The dynamic capabilities view complements these perspectives. Dynamic capabilities refer to a firm's ability to integrate, build and reconfigure competences to address changing environments (Teece et al., 1997), and can be disaggregated into sensing, seizing and reconfiguring (Teece, 2007). Warner and Wäger (2019) show that digital transformation requires building specific dynamic capabilities — digital sensing, digital seizing and digital transforming — through an ongoing process of strategic renewal. In the port context, Kishore et al. (2025) find that dynamic capabilities are associated with shipping port performance through sustainability practices, while Mara and Mokoena (2024) note that research on the digital dynamic capabilities of ports remains scarce.

1.2. Digital maturity and port performance

Port digital maturity designates the extent to which a port community has adopted digital technologies across the informational layer (paperless procedures, data exchange), the operational layer (automation, real-time tracking) and the analytical layer (data analytics, artificial intelligence) (Philipp, 2020). Port performance is understood here as a multidimensional construct encompassing operational, economic, environmental and social dimensions (Lim et al., 2019; O'Connor et al., 2019).

Regarding **operational performance**, digital platforms improve the coordination of vessel calls and the visibility of cargo flows. Caldeirinha et al. (2020), surveying 153 Portuguese port experts, find that six characteristics of port community systems are

related to port performance, and Jiang et al. (2023) show, for the Qingdao port community, that port-centric information integration affects port performance through the operational capability of the community. Nguyen and Pham (2026) report a correlation of 0.83 between a digital transformation index and the operational efficiency of ten Southeast Asian ports. Regarding **economic performance**, digital procedures reduce transaction costs (Williamson, 1979), and Carlan et al. (2016) establish a positive cost–benefit balance of port community systems for each participating actor. Li et al. (2025), using a difference-in-differences design, estimate that the digital transformation of Tangshan Port increased cargo throughput by about 14.5% and container throughput by about 40.2%, and Zhao et al. (2026) find that the big data analytics capability of container ports is most strongly associated with financial performance. Regarding **environmental performance**, digital coordination reduces waiting times and associated fuel consumption (Poulsen & Sampson, 2020), and Yuan et al. (2026) report that digital economy development is associated with lower port emissions in Chinese coastal ports, although Giuliano and O'Brien (2007) found no reduction in truck queues after the introduction of an appointment system in Los Angeles and Long Beach. Regarding **social performance**, the evidence is ambivalent: automation transforms port work and skill requirements (Gekara & Nguyen, 2018) and has been associated with work intensification in Antwerp (Bottalico, 2022), while digitalisation initiatives in African ports have favoured technical over social dimensions (Almeida & Okon, 2025). We nevertheless retain the conventional positive expectation for all four dimensions:

> **H1–H4.** The digital maturity of the port community is positively associated with (H1) operational, (H2) economic, (H3) environmental and (H4) social port performance.

1.3. The mediating role of digital dynamic capabilities

Digital maturity is a stock of technological resources, whereas performance depends on how organisations mobilise and renew these resources. The resource-based literature shows that resources affect performance through the capabilities they enable (Teece, 2007), and digital technologies may in turn support the development of capabilities to sense opportunities, seize them and reconfigure processes (Warner & Wäger, 2019). In ports, Jiang et al. (2023) find that the effect of information integration on performance

passes through a community capability, and Kishore et al. (2025) link dynamic capabilities to port performance. We therefore expect:

> **H5.** Digital dynamic capabilities mediate the relationship between digital maturity and port performance.

1.4. The moderating role of port community governance

Because the port is a community of independent organisations, the value of shared digital platforms depends on coordination among them. The World Bank's survey of African ports identifies public facilitation policies as the most influential factor of digital maturity (World Bank et al., 2023), and Sakita et al. (2024) identify institutional obstacles — inter-agency constraints, system-ownership conflicts and political influence — that slow port digital transformation in an emerging economy. Sirajuddin et al. (2026) find that integrated port governance and digitalisation jointly affect port logistics performance in Indonesia, and Sakita (2026) shows that inter-organisational collaboration is a core dimension of digital transformation in a developing-country port. Complementarity theory implies that the same digital investment yields more where coordination is effective (Melville et al., 2004):

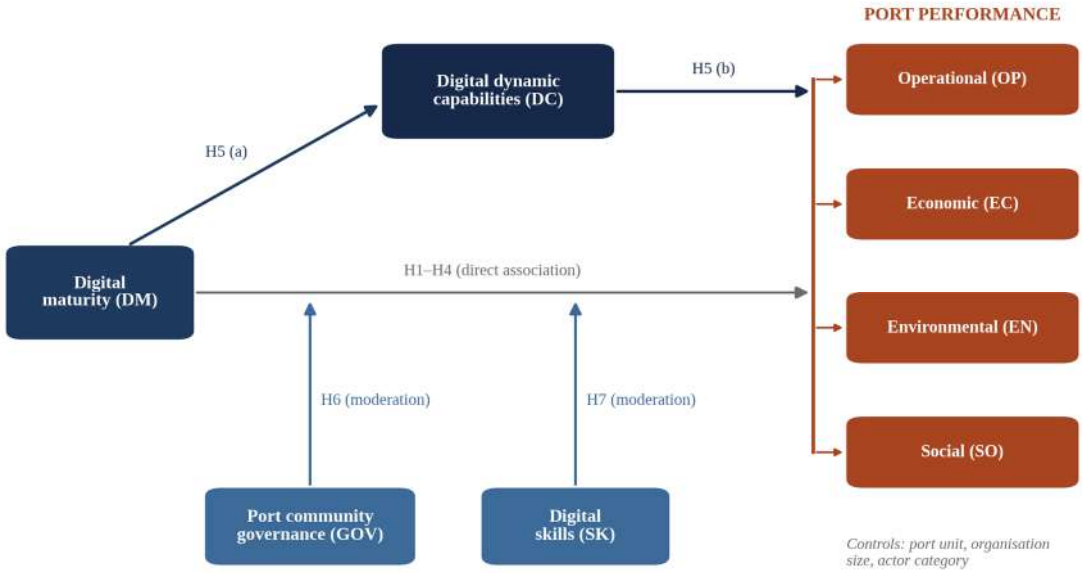
> **H6.** The quality of port community governance positively moderates the relationship between digital maturity and port performance.

1.5. The moderating role of digital skills

Complementarity theory also emphasises human capital: information technology investments are most productive when combined with organisational investments and skills (Brynjolfsson & Hitt, 2000). In container terminals, computerisation and automation have changed the content of work and raised skill requirements (Gekara & Nguyen, 2018), and Sirajuddin et al. (2026) report that certified worker competence has a larger total effect on port logistics performance (0.458) than digital infrastructure and systems (0.281). Users who master digital tools and can exploit the data they produce should therefore extract more value from a given level of digital maturity:

> **H7.** Digital skills positively moderate the relationship between digital maturity and port performance.

Figure 1. Research model. DM = digital maturity; DC = digital dynamic capabilities; GOV = port community governance; SK = digital skills.



Source: Authors.

2. Methodology

2.1. Research setting

The Moroccan port system comprises two institutional models. Following the 2006 port reform, ports such as Casablanca, Jorf Lasfar, Agadir, Mohammedia, Safi and Nador are regulated by the National Ports Agency under a landlord model (Agence Nationale des Ports, 2015), and their procedures are digitalised through the national single window PortNet. Tanger Med is managed by a dedicated authority and operates its own port community system, which made paperless port passage mandatory on 15 February 2022 (Tanger Med Port Community System, 2022). Tanger Med's container throughput rose from about 3.5 million twenty-foot equivalent units (TEU) in 2018 to 11.1 million TEU in 2025 (Tanger Med Port Authority, 2019, 2026). The two units were therefore treated as contrasting embedded units of a single case (Yin, 2018).

2.2. Sample and data collection

The population consists of organisations belonging to the port communities of Tanger Med and of the ANP ports, represented by a manager involved in port operations or digital projects. In the absence of an exhaustive sampling frame, purposive sampling with quotas by port and actor category was used, as in comparable studies (Kishore et al., 2025; Sirajuddin et al., 2026). The questionnaire was administered online and on

paper between 2 March and 10 May 2026. One hundred and fifty usable responses were obtained, with no missing values on construct items and no straight-lining. Table 1 presents the sample profile.

Table 1. Sample profile (n = 150)

Variable	Category	n	%
Port	Tanger Med	56	37.3
	Casablanca	38	25.3
	Jorf Lasfar	20	13.3
	Other ANP ports (Agadir, Mohammedia, Nador, Safi, other)	36	24.0
Actor category	Freight forwarders and customs brokers	39	26.0
	Terminal operators	24	16.0
	Shippers	24	16.0
	Shipping agents and carriers	19	12.7
	Road hauliers	14	9.3
	Port authorities	12	8.0
	Public administrations (customs, inspection)	10	6.7
	Other	8	5.3
Organisation size	Fewer than 50 employees	45	30.0
	50–249	49	32.7
	250–999	41	27.3
	1,000 or more	15	10.0
Seniority in the port sector	Mean (SD)	13.3 years (6.2)	

Source: Authors' survey data.

2.3. Measures

All items were derived from published scales or port-specific indices and measured on five-point Likert scales (1 = strongly disagree; 5 = strongly agree). Digital maturity (DM, six items) covers paperless procedures, automatic data exchange, automation, real-time tracking, analytics and artificial intelligence, and electronic payment, based on Philipp (2020), Molavi et al. (2020), Triska et al. (2024) and Caldeirinha et al. (2020). Digital dynamic capabilities (DC, six items) cover sensing, seizing and reconfiguring, adapted from Kump et al. (2019) and Wilden et al. (2013) and transposed to the digital domain following Warner and Wäger (2019). Port community governance (GOV, four items) covers information sharing, coordination by the port authority, data governance rules and trust, adapted from Paulraj et al. (2008), Jiang et al. (2023) and Sirajuddin et al. (2026). Digital skills (SK, four items) were adapted from van Deursen et al. (2016) and Gekara and Nguyen (2018). The four performance dimensions capture the change observed over the previous three years: operational (OP, five items) and economic

performance (EC, four items) were adapted from Woo et al. (2011), Ha et al. (2019), UNCTAD (2016) and Kishore et al. (2025); environmental performance (EN, four items) from Lu et al. (2016), Puig et al. (2014) and Lim et al. (2019); and social performance (SO, four items) from Lim et al. (2019), Lu et al. (2016) and Brooks and Schellinck (2013). Port unit, organisation size and actor category were included as control variables. The instrument was validated by an expert panel, translated and back-translated between French and Arabic (Brislin, 1970), and pre-tested. Procedural remedies against common method bias — anonymity, separation of predictor and criterion blocks, and neutral wording — were applied (Podsakoff et al., 2003).

Digital maturity, governance and port performance are properties of the port community, whereas they were measured through the perceptions of individual key informants. Following the referent-shift logic of composition models (Chan, 1998), items referred to the respondent's port community rather than to the respondent's own organisation, but individual responses were not aggregated to the port level. Construct scores are therefore interpreted as members' assessments of their community, not as community-level properties (Klein & Kozlowski, 2000); the implications of this choice are discussed in the Conclusion.

2.4. Analytical strategy

The model was estimated with partial least squares structural equation modelling (PLS-SEM), which is suited to prediction-oriented models with composite constructs and moderate sample sizes (Hair et al., 2019). The analysis follows the protocol of Kishore et al. (2025) and the reporting guidelines of Hair et al. (2019), and was implemented in Python using the Lohmöller algorithm with path weighting. Significance was assessed with bias-corrected and accelerated (BCa) bootstrap confidence intervals (CIs) based on 5,000 resamples. Interaction terms were created with the two-stage approach (Hair et al., 2022), and conditional associations were probed with simple slopes and Johnson–Neyman regions of significance (Hayes, 2018; Spiller et al., 2013). Mediation was assessed with specific indirect effects and classified according to Zhao et al. (2010). Because the model includes sixteen hypothesis tests, p-values were adjusted with Holm's (1979) procedure. Given the cross-sectional and perceptual design, structural coefficients are interpreted as associations; terms such as “effect size”, “indirect effect” and “total effect” are used in their statistical sense and do not imply causality.

Several robustness checks were pre-specified: ordinary least squares (OLS) with heteroscedasticity-consistent (HC3) standard errors; estimation without controls; a quadratic term to detect non-linearity; Gaussian copulas to detect endogeneity (Becker et al., 2022); the measurement invariance of composite models (MICOM) procedure and permutation-based multigroup analysis (MGA) (Henseler et al., 2016); and predictive relevance with PLSpredict (Shmueli et al., 2019). Because respondents from the same port partly assess the same port's performance, the non-independence of observations was addressed by computing intraclass correlations (ICCs), by re-estimating the models with port-clustered standard errors evaluated with a wild cluster bootstrap with Webb weights suited to few clusters (Cameron et al., 2008; Webb, 2023), and by a random-intercept multilevel model. Finally, digital maturity was re-estimated as a formative (Mode B) composite including all six items, and the model was re-estimated on the subsample of respondents best placed to assess port performance (port authorities, terminal operators, shipping agents, administrations and other actors; n = 73).

A priori power analysis based on the non-central F distribution indicates that, with 80% power at $\alpha = .05$, about 118 observations are required to detect a single path (direct or interaction) of size $f^2 = 0.068$, 227 for $f^2 = 0.035$ and 395 for $f^2 = 0.02$ (Faul et al., 2009). The sample is thus adequate for direct effects and medium interactions but not for the smallest effects, whose non-significance must be read as inconclusive. Accordingly, a non-significant hypothesis is labelled “inconclusive” when its point estimate corresponds to a small but non-negligible effect ($f^2 \geq 0.015$) that the sample cannot reliably detect, and “not supported” when its point estimate is negligible ($f^2 < 0.01$) or, for indirect effects, when the CI is narrow and centred on zero.

3. Results

3.1. Preliminary analyses and common method bias

Item skewness ranged from −0.63 to 0.00 and kurtosis from −0.88 to −0.02. The Kaiser–Meyer–Olkin index (0.848) and Bartlett's test ($\chi^2 = 2{,}684.2$; df = 595; $p < .001$) confirmed the factorability of the data. Harman's single factor explained 25.1% of the variance, and full collinearity variance inflation factors (VIFs) ranged from 1.11 to 1.70, below the 3.3 threshold (Kock, 2015). These diagnostics suggest that common method variance is not a major concern, although Harman's test is weak and no marker variable was available to correct for it (Podsakoff et al., 2012). Early (n = 105) and late (n = 45)

respondents did not differ on any construct ($p \geq .099$), which argues against non-response bias (Armstrong & Overton, 1977).

3.2. Measurement model

Two items had loadings well below 0.708 in the initial estimation: DM5 (analytics and artificial intelligence; 0.600) and SO2 (occupational safety; 0.497). They were removed because their removal increased the average variance extracted (AVE) of their constructs (Hair et al., 2019). One digital dynamic capabilities item, whose loading (0.696) was marginally below the threshold, was retained because indicators loading between 0.40 and 0.708 should be removed only when this raises reliability or AVE above their thresholds (Hair et al., 2022), which the construct already exceeded (AVE = 0.628; ρ_C = 0.910). As Table 2 shows, the final loadings ranged from 0.696 to 0.908, Cronbach's alpha from 0.790 to 0.882, composite reliability (ρ_C) from 0.873 to 0.910, reliability coefficient ρ_A from 0.824 to 0.895, and all AVEs exceeded 0.50. Discriminant validity was supported by the Fornell–Larcker criterion (Fornell & Larcker, 1981), cross-loadings and a maximum heterotrait–monotrait ratio (HTMT) of 0.591, below 0.85 (Henseler et al., 2015).

The reliability values of social performance require clarification. For this construct, ρ_A (0.889) exceeds ρ_C (0.873), whereas ρ_A normally lies between Cronbach's alpha and ρ_C (Dijkstra & Henseler, 2015). The values reported in Table 2 were rechecked and are internally consistent, since the reported AVE and ρ_C follow from the item loadings. The anomaly signals unequal indicator weights: the construct retains only three indicators, whose loadings range from 0.745 to 0.908. For this reason, the reliability of social performance is judged on the more conservative coefficients, alpha (0.790) and ρ_C (0.873), both of which exceed 0.70; the construct is nonetheless interpreted with caution in what follows.

The removal of DM5 also deserves comment, because analytics and artificial intelligence form the analytical layer of port digital maturity (Philipp, 2020). Its weak loading indicates that, in the communities studied, this layer does not vary together with the informational and operational layers. If digital maturity develops through successive stages, as maturity models suggest (Triska et al., 2024), the analytical layer may still be emerging and unevenly adopted across actors. As a consequence, the reflective DM construct used in the main model mainly captures procedural and operational digital

maturity, and its results cannot be extended to advanced analytics. The formative specification including DM5 (Section 3.5) leaves the conclusions unchanged, which shows that the results do not depend on this removal, but it does not isolate the specific contribution of analytics.

Table 2. *Measurement model (n = 150)*

Construct	Items	Loadings	α	ρ_A	ρ_C	AVE	Max. HTMT
Digital maturity (DM)	5	0.791–0.827	0.869	0.871	0.906	0.658	0.569
Digital dynamic capabilities (DC)	6	0.696–0.844	0.882	0.895	0.910	0.628	0.569
Governance (GOV)	4	0.785–0.837	0.827	0.836	0.885	0.658	0.442
Digital skills (SK)	4	0.796–0.857	0.857	0.867	0.903	0.700	0.556
Operational performance (OP)	5	0.733–0.840	0.861	0.869	0.900	0.643	0.591
Economic performance (EC)	4	0.712–0.850	0.821	0.839	0.881	0.650	0.591
Environmental performance (EN)	4	0.767–0.875	0.822	0.824	0.883	0.654	0.562
Social performance (SO)	3	0.745–0.908	0.790	0.889[a]	0.873	0.697	0.267

Note. Items DM5 and SO2 removed. α = Cronbach's alpha; ρ_A = Dijkstra–Henseler reliability coefficient; ρ_C = composite reliability; AVE = average variance extracted; HTMT = heterotrait–monotrait ratio (highest value for the construct). [a] For social performance, ρ_A exceeds ρ_C because of unequal indicator weights (see text); reliability is assessed on α and ρ_C.

Source: Authors' calculations.

3.3. Structural model and hypothesis tests

Inner VIFs were below 1.62. The standardised root mean square residual (SRMR) was 0.063, below the 0.08 threshold proposed by Hu and Bentler (1999), a cut-off that is only indicative for PLS-SEM (Hair et al., 2019). The model explains 39.2% of the variance of digital dynamic capabilities, 42.3% of operational, 38.5% of economic, 29.3% of environmental and 11.3% of social performance (adjusted $R^2 = 0.014$ for the latter). PLSpredict yielded positive $Q^2_{predict}$ values for all indicators, and the PLS model outperformed the linear benchmark for all of them, although predictive power was weak for social performance (Shmueli et al., 2019). Table 3 and Figure 2 report the hypothesis tests.

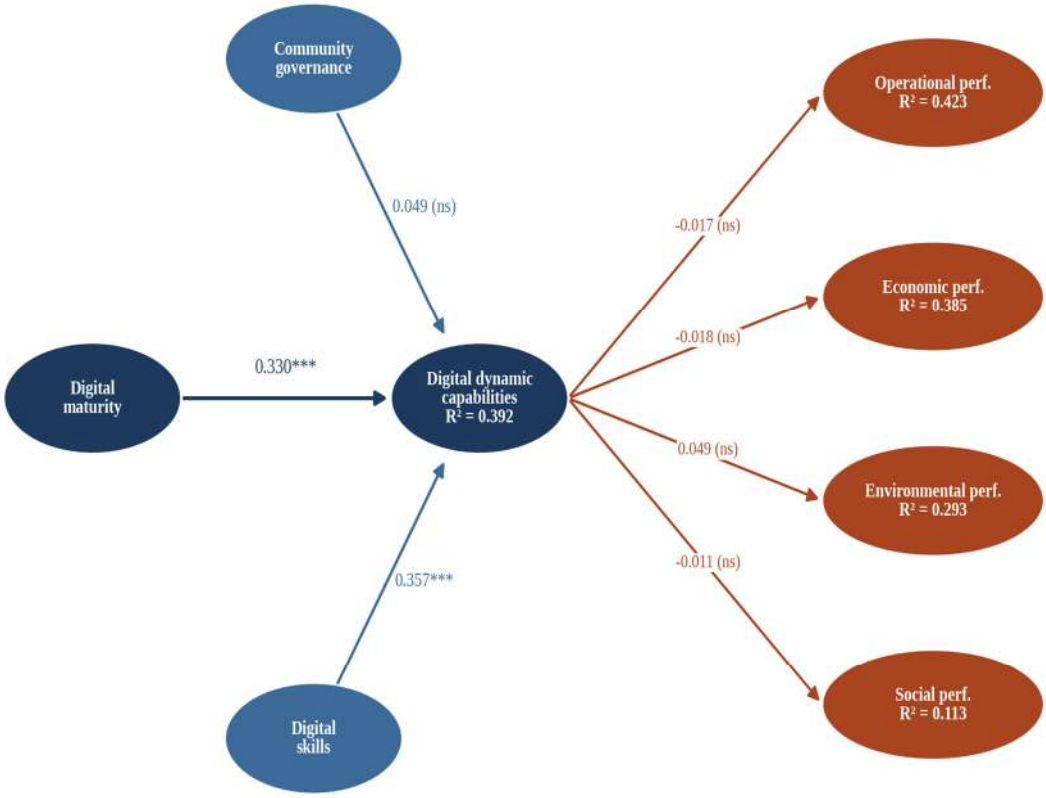
Table 3. Hypothesis tests (n = 150; 5,000 bootstrap resamples)

Hyp.	Path	β	t	95% BCa CI	Holm p	f^2	Decision
H1	DM → OP	0.344	4.03	[0.178, 0.512]	.001	0.124	Supported
H2	DM → EC	0.419	4.34	[0.211, 0.591]	< .001	0.172	Supported
H3	DM → EN	0.413	5.08	[0.237, 0.557]	< .001	0.146	Supported
H4	DM → SO	0.160	1.65	[−0.060, 0.323]	.770	0.017	Inconclusive
H5a	DM → DC → OP	−0.006	0.16	[−0.066, 0.073]	1.000	—	Not supported
H5b	DM → DC → EC	−0.006	0.18	[−0.062, 0.063]	1.000	—	Not supported
H5c	DM → DC → EN	0.016	0.49	[−0.047, 0.086]	1.000	—	Not supported
H5d	DM → DC → SO	−0.004	0.09	[−0.084, 0.073]	1.000	—	Not supported
H6a	DM × GOV → OP	0.139	1.95	[0.004, 0.284]	.457	0.025	Fragile
H6b	DM × GOV → EC	0.277	4.06	[0.146, 0.409]	< .001	0.093	Supported
H6c	DM × GOV → EN	0.130	1.66	[−0.024, 0.280]	.770	0.018	Inconclusive
H6d	DM × GOV → SO	0.050	0.52	[−0.136, 0.232]	1.000	0.002	Not supported
H7a	DM × SK → OP	0.226	3.06	[0.077, 0.368]	.024	0.076	Supported
H7b	DM × SK → EC	0.276	3.79	[0.137, 0.422]	.002	0.106	Supported
H7c	DM × SK → EN	0.175	2.40	[0.041, 0.325]	.166	0.037	Fragile
H7d	DM × SK → SO	0.081	0.90	[−0.085, 0.260]	1.000	0.006	Not supported

Note. Hyp. = hypothesis; BCa = bias-corrected and accelerated; CI = confidence interval. A hypothesis is supported when the 95% BCa CI excludes zero and the Holm-adjusted p-value is below .05, and fragile when only the first criterion is met. When neither criterion is met, it is labelled inconclusive when its point estimate corresponds to a small but non-negligible effect ($f^2 \geq 0.015$: H4, H6c) that the sample cannot reliably detect (about 395 observations would be needed for 80% power at $f^2 = 0.02$), and not supported when the point estimate is negligible ($f^2 < 0.01$: H6d, H7d) or, for indirect effects (H5a–H5d), when the CI is narrow and centred on zero. All models control for port unit, organisation size and actor category.

Source: Authors' calculations.

Figure 2. Estimated structural model (n = 150). Standardised coefficients; *** p < .001; ** p < .01; * p < .05; ns = not significant (unadjusted bootstrap p-values; Holm-adjusted values are reported in Table 3). Control variables not shown.




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Direct DM → performance (H1–H4) and moderation terms (H6–H7)
OP : 0.344***   ×GOV : 0.139 (ns)   ×SK : 0.226**
EC : 0.419***   ×GOV : 0.277***   ×SK : 0.276***
EN : 0.413***   ×GOV : 0.130 (ns)   ×SK : 0.175*
SO : 0.160 (ns)   ×GOV : 0.050 (ns)   ×SK : 0.081 (ns)
Indirect effects via DC (H5): OP -0.006 (ns) ; EC -0.006 (ns) ; EN 0.016 (ns) ; SO -0.004 (ns)
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Source: Authors' calculations.

Digital maturity is positively and significantly associated with operational, economic and environmental performance (H1–H3), with small-to-medium effect sizes (f^2 between 0.124 and 0.172); total effects amount to 0.338, 0.413 and 0.429, respectively. Because the model contains interaction terms, these coefficients represent the association of digital maturity with performance when governance and skills are at their mean, not unconditional associations (Aiken & West, 1991; Hayes, 2018). Digital maturity is not significantly associated with social performance (H4). Given the small point estimate ($\beta = 0.160$; $f^2 = 0.017$), the low explanatory power for this construct (adjusted $R^2 = 0.014$) and its reliability anomaly, this result is classified as inconclusive rather than as evidence of no association.

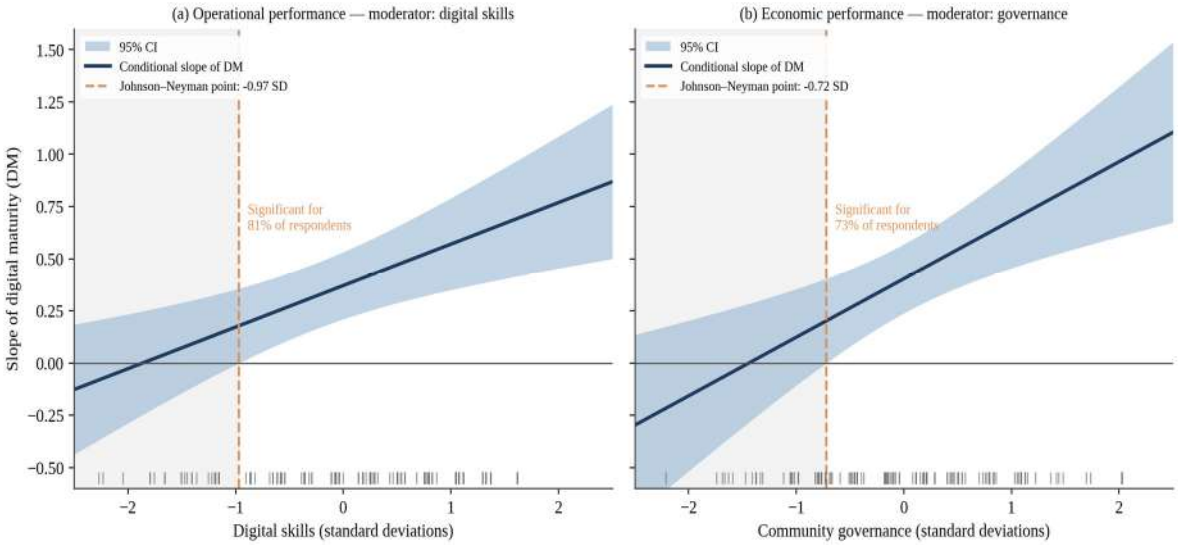
H5 is not supported. Digital maturity is associated with digital dynamic capabilities (β = 0.330; 95% CI [0.173, 0.484]), but these capabilities are not associated with any performance dimension (β between −0.018 and 0.049). Following Zhao et al. (2010), the pattern corresponds to direct-only non-mediation. This null result is informative: the confidence intervals of the indirect effects are narrow (about ±0.07 around zero) and rule out an indirect effect of substantive size. Digital dynamic capabilities are more strongly associated with digital skills (β = 0.358; 95% CI [0.205, 0.493]) than with digital maturity, while governance is not associated with them (β = 0.049).

The moderation hypotheses are partially supported. Digital skills strengthen the association of digital maturity with operational (H7a) and economic performance (H7b), and these results survive the Holm correction; the moderation of environmental performance (H7c) does not and is considered fragile. Skills have no direct association with performance. Governance strengthens the association with economic performance (H6b); its interaction with operational performance (H6a) does not survive the correction. Governance is, however, directly associated with operational performance (β = 0.175; 95% CI [0.002, 0.318]).

3.4. Conditional associations

Figure 3 displays the Johnson–Neyman analysis. The association between digital maturity and operational performance is significant when digital skills exceed −0.97 standard deviations (SD), that is, for 81% of respondents; the simple slope rises from 0.118 at one SD below the mean of skills to 0.570 at one SD above. The association with economic performance is significant when governance exceeds −0.72 SD (73% of respondents) and rises from 0.142 to 0.696 between these two levels. These simple slopes are derived from the PLS-SEM coefficients, whereas the confidence bands and Johnson–Neyman points in Figure 3 come from the OLS re-estimation, which explains the slight differences between the slopes shown in the figure and those reported here. In other words, for roughly the fifth of respondents reporting the weakest skills and the quarter reporting the weakest coordination, digital maturity is not associated with better perceived performance.

Figure 3. Conditional association of digital maturity with operational performance across levels of digital skills (panel a) and with economic performance across levels of governance (panel b), with 95% confidence bands and Johnson–Neyman points (n = 150). OLS estimates on standardised construct scores including the three controls; rug marks show the observed distribution of the moderator.



Source: Authors' calculations.

3.5. Robustness and non-independence of observations

Table 4 summarises the robustness checks and supplementary analyses. The OLS estimation reproduces all conclusions except that the governance × digital maturity interaction on operational performance becomes significant (β = 0.189; p = .011). Removing the controls changes the coefficients by at most 0.056. Quadratic terms are not significant (p ≥ .176), and Gaussian copula terms are not significant (p ≥ .156), although copula tests have low power in samples of this size and do not address omitted variables or reverse causality (Becker et al., 2022). MICOM established compositional invariance (minimum compositional correlation 0.977), and the multigroup analysis detected no difference between Tanger Med (n = 56) and ANP ports (n = 94) (p ≥ .261), which, given the subsample sizes, means that no difference was detected rather than that relationships are homogeneous.

Table 4. Robustness checks and supplementary analyses

Analysis	Procedure	Main result	Implication
Alternative estimator	OLS on mean scores, HC3 standard errors	Same conclusions; DM × GOV → OP significant (p = .011)	Robust; H6a fragile
Controls	Model without controls	Maximum coefficient change 0.056	Robust
Non-linearity	Quadratic DM term	p ≥ .176	Linear relationships
Endogeneity	Gaussian copulas	p ≥ .156	No endogeneity detected (low power)
Group differences	MICOM; permutation MGA	Compositional invariance; p ≥ .261	No difference detected
Clustering by port	Intraclass correlations	0.000 (SK) to 0.172 (DM); ≤ 0.061 for performance	Moderate non-independence for DM
Clustered inference	Port-clustered standard errors; wild cluster bootstrap (8 clusters)	H1–H3: p ≤ .006; DM × GOV and DM × SK on OP and EC: p ≤ .023; on EN: p ≥ .164	H1–H3, H6b, H7a, H7b confirmed; H7c fragile
Multilevel model	Random intercept by port	DM × GOV → EC p < .001; → OP p = .082; DM × SK → OP, EC, EN p ≤ .027	Conclusions unchanged; H6a fragile
Formative DM	Mode B, six items incl. DM5	DM → OP, EC, EN: 0.368–0.427; DM × SK significant on OP, EC, EN; DM × GOV significant on EC only	Conclusions unchanged
Best-placed respondents	Subsample, n = 73	DM → EC 0.314 and DM → EN 0.304 significant; DM → OP 0.230 (ns); DM × GOV → EC 0.397 significant	Direction preserved; reduced power

Note. OLS = ordinary least squares; HC3 = heteroscedasticity-consistent standard errors (type 3); MICOM = measurement invariance of composite models; MGA = multigroup analysis; ns = not significant.

Source: Authors' calculations.

Three lessons emerge. First, the core results — the associations of digital maturity with operational, economic and environmental performance, the moderation by skills of the operational and economic associations, and the moderation by governance of the economic association — hold across all estimations. Second, the moderation of environmental performance by skills (H7c) and of operational performance by governance (H6a) vary across estimations and are fragile. Third, the association with environmental performance remains significant among the respondents best placed to assess it, which mitigates — without removing — the concern that respondents without access to environmental data may rate their port favourably overall (a halo effect).

4. Discussion

4.1. Theoretical implications

The first implication concerns the **performance dimensions**. Digital maturity is associated with operational, economic and environmental performance, consistent with studies on port community systems (Caldeirinha et al., 2020), information integration (Jiang et al., 2023) and digital transformation (Li et al., 2025; Nguyen & Pham, 2026). The strongest association concerns economic rather than operational performance, which echoes Zhao et al. (2026), who find that big data analytics capability is most strongly associated with the financial performance of container ports. Because the analytical item (DM5) was removed from the digital maturity measure, this convergence concerns the outcome dimension rather than the type of technology. A plausible interpretation is that operational gains may be bounded by physical constraints — berths, access roads, inspections — that digitalisation does not remove, whereas transaction-cost savings can materialise as soon as procedures are dematerialised (Williamson, 1979). The congestion experienced by the port of Casablanca from late 2025, despite largely dematerialised procedures, illustrates this boundary (Khatla, 2026; Le360, 2026). The non-significant association with social performance calls for particular caution. The construct relies on three items, shows a reliability anomaly and is weakly explained (adjusted $R^2 = 0.014$), and its point estimate ($\beta = 0.160$; $f^2 = 0.017$) lies in a range the sample cannot reliably detect; the result therefore does not establish that digital maturity is unrelated to social performance. With this reservation, it is compatible with the ambivalent effects of automation on port work (Bottalico, 2022; Gekara & Nguyen, 2018) and with the technical bias of digitalisation initiatives in African ports (Almeida & Okon, 2025), but any theoretical reading of H4 should await better measurement and larger samples.

The second implication concerns **complementarities**. The moderating role of digital skills is among the most robust findings of the study and extends the complementarity argument of Brynjolfsson and Hitt (2000) and Melville et al. (2004) to port communities in an emerging economy. Skills are not directly associated with performance; they condition the association between digital maturity and perceived performance, to the point that digital maturity is unrelated to perceived performance among respondents with the weakest skills. Governance plays a dual role: it conditions the association between digitalisation and economic performance and is directly

associated with operational performance, in line with Sirajuddin et al. (2026) and Sakita (2026). This suggests that coordination is both an enabler of digital value and a performance resource in its own right.

The third implication concerns the **level of analysis of dynamic capabilities**. The absence of mediation contrasts with Kishore et al. (2025), who examined the dynamic capabilities of port organisations themselves. In the present study, capabilities were measured at the level of each community member — forwarders, shippers, hauliers — and related to the performance of the port, which is a collective outcome. It is likely that port performance depends on the capabilities of the port authority, the community platform and the state more than on those of individual members. This null result, estimated precisely, invites researchers to specify the level at which the dynamic capabilities view is transposed to port settings rather than to treat port communities as aggregates of firms.

4.2. Practical implications

For port authorities and single-window operators, the results suggest that the governance of shared data — rules on access, ownership and use, coordination of common projects and trust — should accompany digital platforms rather than follow them. For terminal operators and other private actors, digital investments should be coupled with user training from the outset, since the association between digital maturity and performance is not significant where skills are weakest. For policymakers, the findings support linking national digital strategies with sector-specific skills programmes and with investment in physical capacity.

Conclusion

This study examined whether, and under which conditions, the digital maturity of a port community is associated with port performance in the Moroccan port system. Using survey data from 150 port community members and PLS-SEM, it finds that digital maturity is positively associated with economic, environmental and operational performance, with small-to-medium effect sizes, whereas its association with social performance is not significant and remains inconclusive. These associations are conditioned by digital skills and, for economic performance, by port community governance, which is also directly associated with operational performance. Digital

dynamic capabilities of community members do not mediate the relationship. The core results are robust to clustered and multilevel inference, multiple-testing correction, a formative specification and a subsample of the best-placed respondents.

Four recommendations follow, keeping in mind that they rest on cross-sectional associations. Port authorities should formalise data-sharing rules in a community charter and publish monthly operational indicators as open data. Single-window operators should pair each new digital service with a mandatory switch-over date and support for users, as practised at Tanger Med (Tanger Med Port Community System, 2022). Private port actors should integrate training into every digital project and measure the return on their digital investments. Policymakers should couple digital investment programmes with physical capacity planning and sector-specific skills programmes.

The study has several limitations. First, the sample of 150 respondents falls short of the 250–300 initially targeted; it detects direct effects and medium interactions but not the smallest effects ($f^2 < 0.04$), whose non-significance is inconclusive. Second, the cross-sectional, perceptual design supports associations rather than causal claims; common method variance could only be diagnosed, and environmental performance ratings may be affected by a halo effect. Third, non-probability sampling limits statistical generalisation. Fourth, digital maturity, governance and port performance are community-level constructs measured through individual perceptions. The intraclass correlation of digital maturity (0.172), which lies between the medium (.10) and large (.25) benchmarks proposed by LeBreton and Senter (2008), shows that respondents from the same port share part of their assessment, but eight port clusters are too few to model these constructs at the community level. The results therefore describe members' perceptions of their community rather than community-level properties, and the relationships could differ at the port level (Klein & Kozlowski, 2000). Fifth, dynamic capabilities were measured at the level of community members, which may explain the absence of mediation. Sixth, the social performance construct retains only three items, shows a reliability anomaly and is weakly explained, which limits the interpretation of H4. Seventh, the removal of the analytics and artificial intelligence item (DM5) means that the digital maturity measure mainly reflects procedural and operational digitalisation, so that the findings do not inform the performance associations of advanced analytics.

Future research should test the model on larger samples with a marker variable and a longitudinal design; estimate the effect of digital interventions, such as paperless port passage, with interrupted time series or synthetic control methods (Abadie et al., 2010) once monthly operational data become available; measure dynamic capabilities at the level of port authorities and community platforms; apply multilevel designs covering enough ports to aggregate community-level constructs; measure the analytical layer of digital maturity as a distinct construct, for instance as big data analytics capability (Zhao et al., 2026); use objective environmental and social indicators and a broader set of social performance items; and compare Morocco with other Mediterranean and African port systems.

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